THRUSt CHAMBER LIFE PREDICTION

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Abstract

The reusable life of the Space Shuttle Main Engine (SSME) is influenced by the cyclic life of the regeneratively liquid cooled main combustion chamber (MCC). During an operational duty cycle the MCC liner is subjected to a large transient thermal gradient that imparts a high thermal cyclic strain to the liner hot gas wall. Life predictions of such chambers have usually been based on low cycle fatigue (LCF) evaluations. Hot-fire testing, however, has shown significant mid-channel wall deformation and thinning during accrued cyclic testing. This phenomenon is termed cyclic creep and appears to be significantly accelerated at elevated temperatures.

An analytical method that models the cyclic creep phenomenon and its application to thrust chamber life prediction is presented. The chamber finite element geometry is updated periodically to account for accrued wall thinning and distortion. Failure is based on the tensile instability failure criterion. Cyclic life results for several chamber life enhancing coolant channel designs are compared to the typically used LCF analysis that neglects cyclic creep. The results show that the usable cyclic creep life is approximately 30 to 50% of the commonly used LCF life.

Introduction

The reusable life of the Space Shuttle Main Engine (SSME) and future engines are greatly influenced by the cyclic life of several major components subjected to high temperature environments. The main combustion chamber (MCC) liner is exposed to an environment that produces a heat flux of approximately 100 BTU/in²·sec in the life limited throat region. To accommodate this high heat flux, the copper base MCC liner is regeneratively cooled through integral rectangular cooling channels. During operational duty cycles (missions) the MCC liner hot gas wall experiences large thermal plastic cyclic strains resulting from a large transient thermal gradient. These cyclic strains influence the fatigue life of the MCC liner hot gas wall.

Low cycle fatigue life is typically a function of the cyclic strain range, the material properties and the operating temperature. The theoretical reusable life is normally determined by the number of strain cycles that can be accrued before initiation of surface
cracks. Hot-fire testing of channel wall combustors at Rocketdyne and NASA Lewis Research Center (LeRC), however, indicates that fatigue is not necessarily the dominate failure mode. Significant mid-channel permanent deformation and wall thinning is witnessed during these hot-fire tests. It is concluded that the failure mode is one of strength once the wall has thinned to its critical thickness. The thinning phenomenon is termed cyclic creep and appears to be significantly accelerated at elevated temperatures. The sensitivity of the phenomenon to surface temperature is evidenced by the non-uniformity of channel wall deformation around the circumference of the combustors.

In 1973, work began at LeRC to systematically investigate the problem of thrust chamber life. The approach was to use cyclic testing under controlled conditions, and with a test procedure specifically designed to study thrust chamber life, finite element analyses were performed to compute strain range. Attempts were made to predict life assuming low cycle thermal fatigue failure mechanics and using life data from universal isothermal laboratory fatigue tests as a reference. This life prediction procedure was generally unsuccessful. Consequently, it was decided that an analytical method that models the observed cyclic creep phenomenon was needed to improve life prediction capability.

An analytical method was developed that periodically updates the chamber finite element geometry to account for accrued wall thinning and distortion. The methodology consists of analyzing the chamber considering more increments in the duty cycle and geometric deformation effects. The geometric deformation formulation allows the analysis to adjust to small geometry changes that occur during each duty cycle and are cumulative in nature. In order to minimize computer time, an extrapolation procedure is utilized. To perform the analysis, five duty cycles are sequentially analyzed and the change in geometric shape is extrapolated to the deformation conditions 15 cycles further on, e.g., 5 cycles + 15 cycles = 20 cycle condition. Using the new geometry, additional duty cycles are analyzed and another extrapolated shape projection made. This technique is continued until failure occurs. Failure is based on the tensile instability failure criterion. Cyclic creep life analysis results for several chamber life enhancing designs, when compared to the typically used low cycle fatigue (LCF) analysis results, show that the usable cyclic creep life is approximately 30 to 50% of the LCF life.
STRUCTURAL ANALYSIS MODEL

CONVENTIONAL LIFE ANALYSIS SCHEMATIC

FATIGUE DAMAGE DETERMINATION

STRESS OR STRAIN - TIME CYCLE

EXPERIMENTAL DATA

INCREMENTAL DAMAGE FOR EACH CYCLE

CYCLIC FATIGUE DAMAGE

CREASE DAMAGE DETERMINATION

CALCULATED STRESS - TIME CYCLE

EXPERIMENTAL STRESS RUPTURE DATA

INCREMENTAL TIME DAMAGE

CREASE DAMAGE

LINEAR DAMAGE RULE

$\phi_f + \phi_c = 1$

PREDICTED LIFE

$n = \Delta \phi_f + \Delta \phi_c$

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Cyclical Creep Life Analysis Approach

- Consider
- Temperature and pressure history
- Jacket radial displacements and axial restraint
- Initial radial liner gap 0.500 mm (0.020 in.)
- Structural model
- Plane strain cross section
- Inelastic material - kinematic hardening
- Geometric distortions
- Creep/relaxation

TYPICAL CHANNEL WALL FAILURE

Temperature & Pressure

Time

Duty cycle, 11 increments

Jacket

Liner

Thermal/structural model

Channel wall thinning

Maximal tensile instability failure due to wall thinning

15 extrapolated duty cycles

5 calculated duty cycles

Duty cycle

40
CYCLIC CREEP LIFE ANALYSIS SCHEMATIC

LOADS
- TEMPERATURE
- PRESSURE
BOUNDARY CONDITIONS

LINEAR MODEL
CURRENT GEOMETRY
& ITERATION AND/OR
INCREMENT DEPENDENT

RESULTS/CYCLE
STRESS, STRAIN,
DISPLACEMENT,
GEOMETRY UPDATE

MULTIPLE
DUTY CYCLES (6)

GEOMETRY
FOR NEXT
SET OF LOAD
CYCLES

FAILURE

LIFE PREDICTION
TENSILE INSTABILITY

PREDICTED
LIFE

NO FAILURE

DISPLACEMENT
EXTRAPOLATION

MODIFY THERMAL
LOADS IF REQUIRED

CHECK GEOMETRY
EFFECT OF
THERMAL LOADS

GEOMETRY
CHANGE

TYPICAL GEOMETRIC SHAPE CHANGE WITH CYCLING

Cycle 5

Cycle 65

Cycle 25

Cycle 85

Cycle 45

Cycle 105

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MID-CHANNEL WALL PERMANENT DEFORMATION (THINNING)

LIFE ENHANCED DESIGNS

1. CONTOURED MID-CHANNEL WALL
2. KEEL RIB (FINS)
3. INCREASED NUMBER OF CHANNELS
4. SLOTTED HOT GAS MID LAND WITH INCREASED CHANNELS

GOALS (REDUCED CYCLIC CREEP)
- REDUCED WALL TEMPERATURE
- REDUCED STRAIN RANGE

BASELINE SSME - MCC

WALL THICKNESS = (USE OF WALL THICKNESS)

Bladed Failure Strain Range

SSME 1000 kg

DUTY CYCLES

300 CHANNELS

540 CHANNELS

300 CHANNELS

460 CHANNELS

300 CHANNELS
COMPARISON OF LIFE ENHANCED DESIGNS

HOT WALL TEMPERATURE

<table>
<thead>
<tr>
<th>Temperature</th>
<th>LCF Life</th>
<th>Cyclic-Creep Life</th>
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<td></td>
<td></td>
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</table>

DESIGN CONDITION (% HG)

<table>
<thead>
<tr>
<th>Design Condition</th>
<th>SSME</th>
<th>Contoured</th>
<th>540 Channel</th>
<th>Keel Rib</th>
<th>Slotted</th>
</tr>
</thead>
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<tr>
<td>6%</td>
<td>100</td>
<td>135</td>
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SUMMARY

- Analytical model provides a refined analysis that models the observed failure mode

- Predicted cyclic-creep life is typically 30 to 50% of the low-cycle-fatigue life

- The most feasible approach to increasing SSME-MCC life is increasing the number of coolant channels